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Light Water Reactor Sustainability Program

Plan to Verify and Validate Multi-Hazard Risk-Informed Margin Management Methods and Tools

Justin L. Coleman
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ABSTRACT

This report describes the development plan for verification and validation (V&V) of multi-hazard risk informed margin management (RIMM) methods and tools. The plan will include using new INL developed tool sets coupled with the new multi-partner Experimental Research Group - External Hazards (ERG-EH) coordinated by the Idaho National Laboratory (INL) within the Risk-Informed Safety Margin Characterization (RISMC) technical pathway of the Light Water Reactor Sustainability Program.

The RISMC pathway is developing a suite of new tools and methods for advanced evaluation of nuclear facility risk. The RISMC toolkit, includes tools and methods focused on evaluation of risk from external hazards (e.g., seismic and flooding events), which have been shown to be dominant risk contributors in probabilistic risk assessments performed for operating nuclear power plants (NPPs). The external events activity within the RISMC pathway is tasked with developing tools and methods focused on evaluation of multi-hazard external risk (e.g, seismic and flooding events). The ERG-EH will provide technical expertise and experimental large-scale testing data needed for development and validation of tools and methods in the RISMC toolkit for external hazard safety evaluations.

The external events activity within RISMC has two key elements: (1) an organizational and research framework provided by INL and (2) a coordinated group of university and national laboratory partners with the complementary expertise and experimental capabilities needed to conduct large-scale external hazard-focused experiments. This cooperative group will allow INL to leverage a range of existing capabilities to meet the unique needs of RISMC tool and method development. In addition, the capabilities of the ERG-EH could be used to address needs of other national laboratories.

Currently, there is limited data available for development and validation of the tools and methods being developed in the RISMC Toolkit for external hazards. The ERG-EH is being developed to obtain high quality, large-scale experimental data used to validate RISMC tools and methods in a timely and cost-effective way. The group of universities and national laboratories that will eventually form the ERG-EH (which is ultimately expected to include both the initial participants and other universities and national laboratories that have been identified) have the expertise and experimental capabilities needed to both obtain and compile existing data archives and perform additional seismic and flooding experiments. The data developed by ERG-EH will be stored in databases within RISMC. These databases will be used to validate the advanced external hazard tools and methods.

The numerical tools under development in RISMC are used to evaluate the impacts that external hazards have on nuclear power plants. These analysis tools will be used to advanced current risk calculation processes and reduce uncertainty in these calculations. To have confidence in the predictive capability of these numerical tools it is important to verify and validate them. To verify and validate numerical tools the user must understand what physics is being used to represent the problem (i.e. constitutive models used to represent the soil and structure), the numerical solver approach used (i.e. finite element), what data already exists that could be used to validate the tools, and what data is needed for validation.

A brief discussion of several near term tests to gather data for validation of both seismic and flooding tools is provided.

ACKNOWLEDGEMENTS

Input on the intellectual and physical capabilities of the external hazards experimental group was provided by each of the six university partners: University at Buffalo, Purdue University, The George Washington University, North Carolina State University, University of Illinois, and Idaho State University. Additionally, Chad Pope, Alison Wells, and David Kamerman from Idaho State University contributed to Section 4.2.

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ACRONYMS

DOE	Department of Energy
ERG-EH	External Hazards Experimental Group
EPRI	Electric Power Research Institute
INL	Idaho National Laboratory
LWRS	Light Water Reactor Sustainability
MOOSE	Multiphysics Object Oriented Simulation Environment
NPP(s)	nuclear power plant(s)
PRA(s)	probabilistic risk assessment(s)
R&D	research and development
RIMM	risk-informed margins management
RISMC	Risk-Informed Safety Margin Characterization
SSCs	structures, systems, and components

Plan to Verify and Validate Multi-Hazard Risk-Informed Margin Management Methods and Tools

1. INTRODUCTION

This report describes the development plan for verification and validation of external hazard methods and tools. Included in that development plan is a new multi-partner Experimental Research Group – External Hazards (ERG-EH) coordinated by the Idaho National Laboratory (INL) within the Risk-Informed Safety Margin Characterization (RISMC) technical pathway of the Light Water Reactor Sustainability (LWRS) Program (Smith et al. 2013). As described in more detail later, the RISMC pathway is developing a suite of new tools and methods (known as the "RISMC toolkit") for advanced evaluation of facility risk. The RISMC toolkit, includes tools and methods focused on evaluation of risk from external hazards (e.g., seismic and flooding events), which have been shown to be dominant risk contributors in probabilistic risk assessments (PRAs) performed for operating nuclear power plants (NPPs).

External hazards are a significant component of interest for the nuclear energy community, and more research is needed to reduce uncertainty and quantify the safety margin at existing and new nuclear facilities. The focus is on developing verified and validated tools that can quantify multi-event external hazard risk.

The resulting process will allow nuclear facility owners to more effectively manage their external hazard risk. Figure 1 illustrates the evolution from today's current approach for quantifying NPP risk to the longer-term goal of virtually quantifying NPP performance. Notice the focus on external hazards such as seismic and flooding.

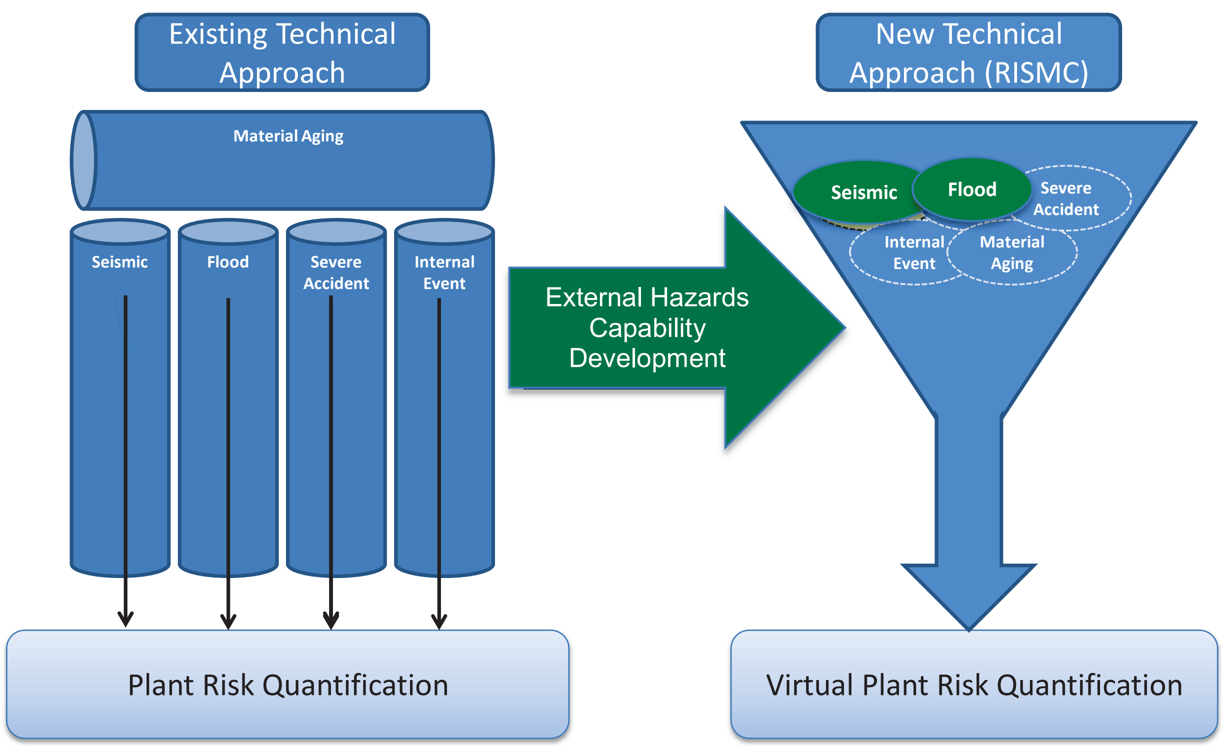

Figure 1. Evolution of NPP External Hazards Risk Assessment and Management

As stated above, advanced external hazard capabilities are needed to provide a better understanding of NPP response during and after external hazard events. Verified and validated methods and tools require research and development in three areas: methods, tools (Numerical Software), and data. Further explanation of the three areas of capability development areas is provided in Table 1.

Table 1. External Hazards Areas of Focus

METHODS	TOOLS (Numerical Software)	DATA
Methods include acceptable numerical approaches and risk-informed evaluation approaches.	Tools development includes using and integrating existing numerical software and developing new software when necessary to support the methods.	Data will be gathered and experimental tests run to validate the methods and tools. Data will be gathered from existing experimental tests and external hazard events at nuclear power plants. Experimental tests will be performed to provide additional validation data.

INL will leverage both the intellectual and physical facilities maintained by other laboratories, various universities, and international entities. A description of the capabilities that will be leveraged is provided in Figure 2.

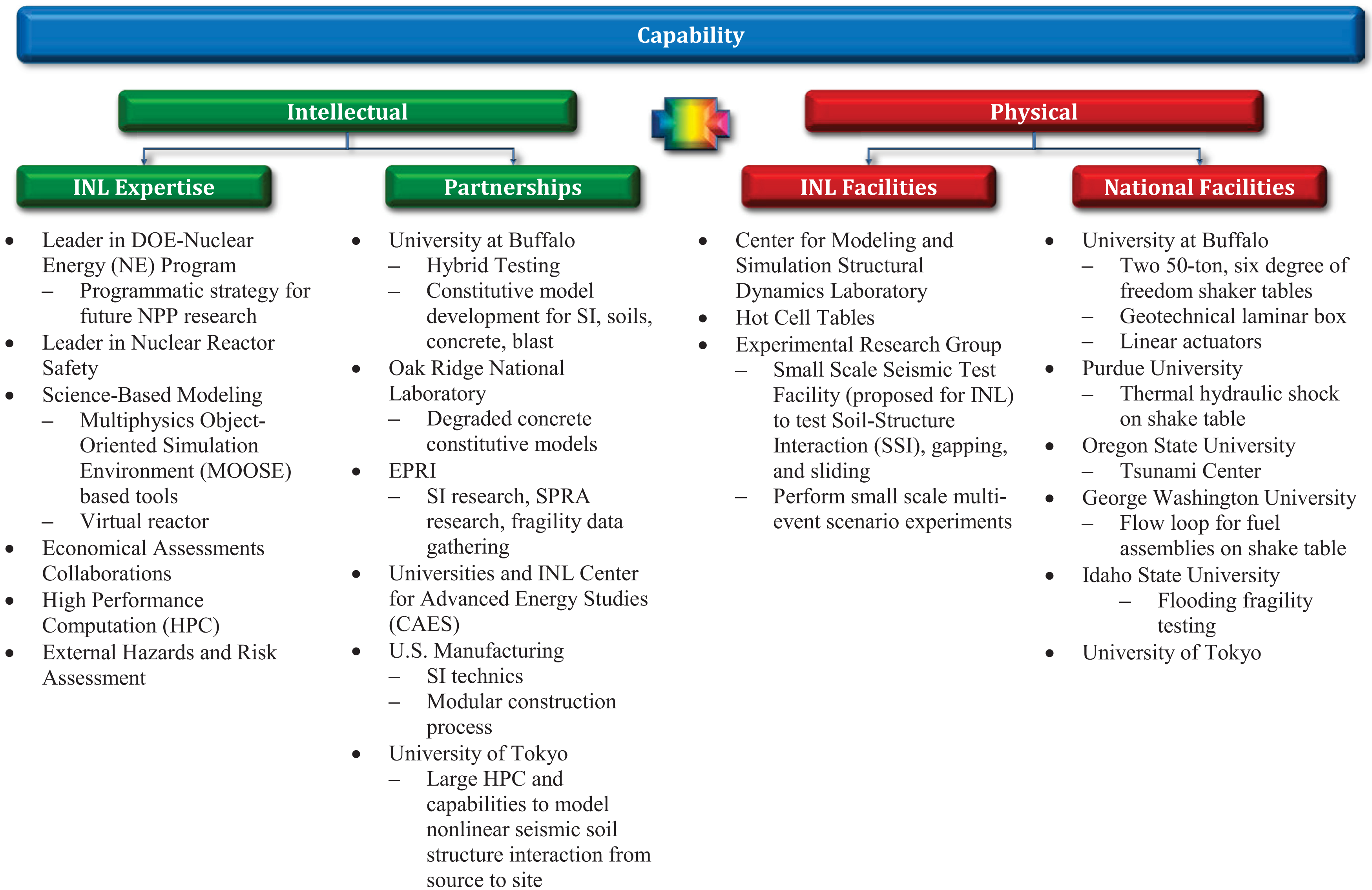

Figure 2. External Hazards Capability

1.1 Overview of the RISMC Toolkit

A systematic approach to the characterization and assessment of safety margins, and the subsequent margins management, represent vital inputs to licensee and regulatory analysis and decision-making. The purpose of the RISMC technical R&D pathway is to develop tools and methods that support plant decisions for risk-informed margins management (RIMM) strategies. The aim of RISMC is to improve the economics of aging management while ensuring the reliability and safety of operating nuclear power plants over periods of extended plant operations.

The goals of the RISMC R&D Pathway are twofold:

(1) Develop and demonstrate a risk-assessment method that is coupled to safety margin quantification that can be used by NPP decision makers as part of RIMM strategies.

(2) Create an advanced RISMC Toolkit that enables more accurate representation of NPP safety margins.

The ERG-EH directly supports goal (2), above, and indirectly supports goal (1) by providing experimental data for the verification of tools within the RISMC Toolkit. The RISMC Toolkit is being built using INL's Multiphysics Object Oriented Simulation Environment (MOOSE) High Performance Computing framework (Gaston et al. 2009). MOOSE is INL's development and runtime environment for the solution of multi-physics systems that involve multiple physical models or multiple simultaneous physical phenomena. Models built on the MOOSE framework can be coupled as needed for solving a particular problem, including the assessment of facility performance when impacted by external hazard phenomena (e.g., seismic or flooding events).

The advanced methods and tools in the RISMC toolkit can be used within a RIMM approach to improve decision making by providing a technical basis to assess both the breadth of real world external hazard scenarios and the potential impacts on the NPP based on the hazard. Importantly, external hazards of interest have a primary impact on the nuclear facility. However, as shown in Figure 3,these primary phenomena may also lead to secondary effects, which have not been assessed in a time based calculation in past practice. Examples of primary impacts of external hazards are seismic shaking, flooding, and high winds. Examples of secondary effects induced by seismic and/or flood events are dam and levy failure, landslide, internal flood, and internal fire. The correlation and temporal relationship of these primary and secondary hazards complicate the determination of safety in any complex facility.

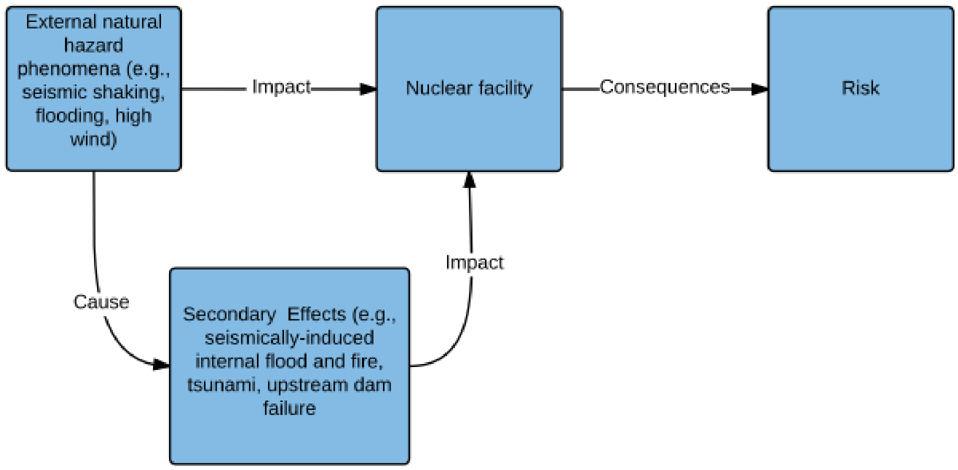

Figure 3: Potential primary and secondary external hazard propagation at NPPs

An example of a scenario that RISMC is uniquely capable of assessing is presented in Figure 5. This scenario includes a seismic event that may lead to failure of a flood protection levee, as in addition to, the safety-related structures, systems and components (SSCs) of the NPP. The scenario involves a primary hazard (seismic shaking) and secondary effects (flooding, both internal and external, and thermal-hydraulic-related effects, including impact to the reactor core). A similar scenario, in which the RIMM approach will be applied at a generic NPP with a flood protection levy and a defined seismic hazard, will be used as a demonstration problem. The analysis will be initiated with potential (i.e., stochastic) seismic events, based on a probabilistic seismic hazard assessment, that produce ground motion at the NPP site. These ground motions will be used to calculate probabilities of SSC failures at the NPP and levy. Based on probabilistic models of the conditional failure of piping systems and the flood protection levy, advanced flooding analysis will be run in locations of interest.

The external events activity within RISMC has two key elements: (1) an organizational and research framework provided by INL and (2) a coordinated group of university and national laboratory partners with the complementary expertise and physical capabilities needed to conduct large-scale external hazard-focused experiments. This second element, known as the ERG-EH, will allow INL to leverage a range of existing capabilities to meet the unique needs of RISMC toolkit development. In addition, the capabilities of the ERG-EH could be used to address needs of other national laboratories. The initial partners in the ERG-EH are identified in Figure 4,below.

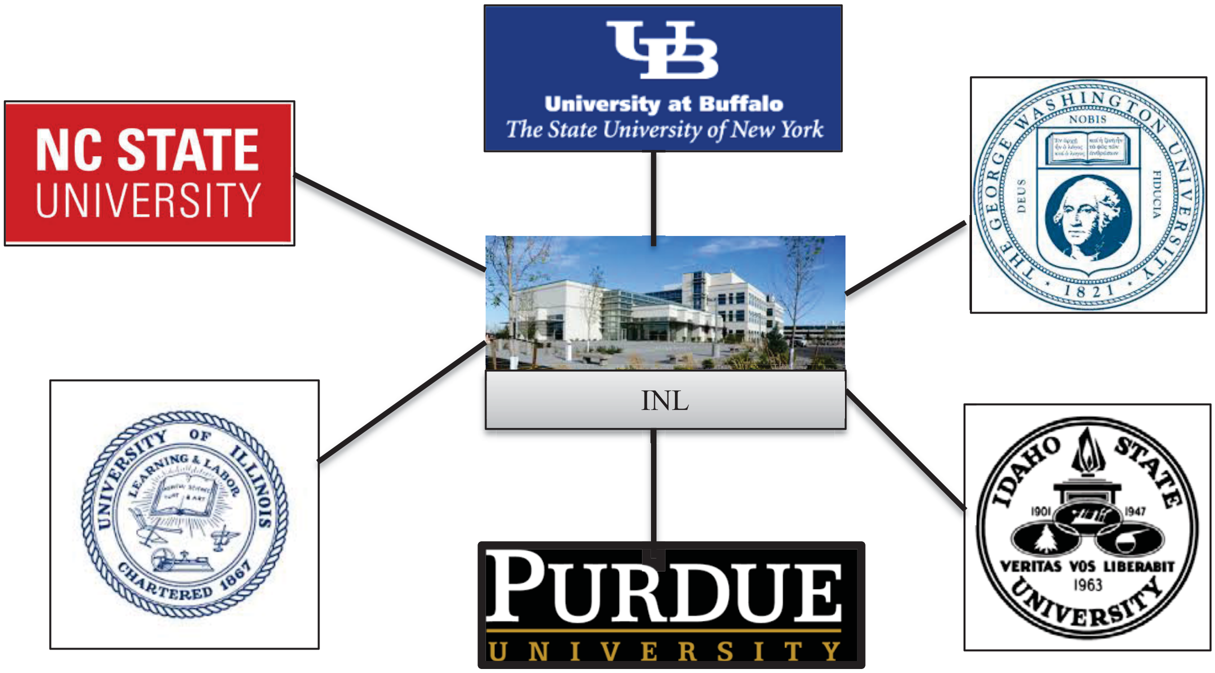

Figure 4: Initial ERG-EH partners

1.2 Outline of this Report

Section 2 of this report provides additional information on the RISMC pathway and LWRS program and describes in more detail the need for the ERG-EH and the role of the ERG-EH within the existing activities. Section 3 describes the ERG-EH intellectual and physical testing capabilities and the structure of the ERG-EH. Section 4 describes near-term large scale testing activities currently under development. Section 5 provides a summary of the report.

2. NEED FOR VERIFICATION AND VALIDATION OF TOOLSETS USED IN THE NUCLEAR INDUSTRY

The RISMC toolkit is used to evaluate the impact of multi-hazard events, such as earthquake ground motions and external and internal flooding, on nuclear facilities. These analysis tools are used to design and perform risk calculations for nuclear facilities. To have confidence in the predictive capability of these numerical tools it is important to verify and validate them. To verify and validate numerical tools the user must understand what physics is being used to represent the problem (i.e. constitutive models used to represent the soil and structure), the numerical solver approach used (i.e. finite element), what data already exists that could be used to validate the tools, and what data is needed for validation. For example the area of interest for numerical modeling of NPP response due to seismic ground motion is shown as a meshed domain in Figure 5.

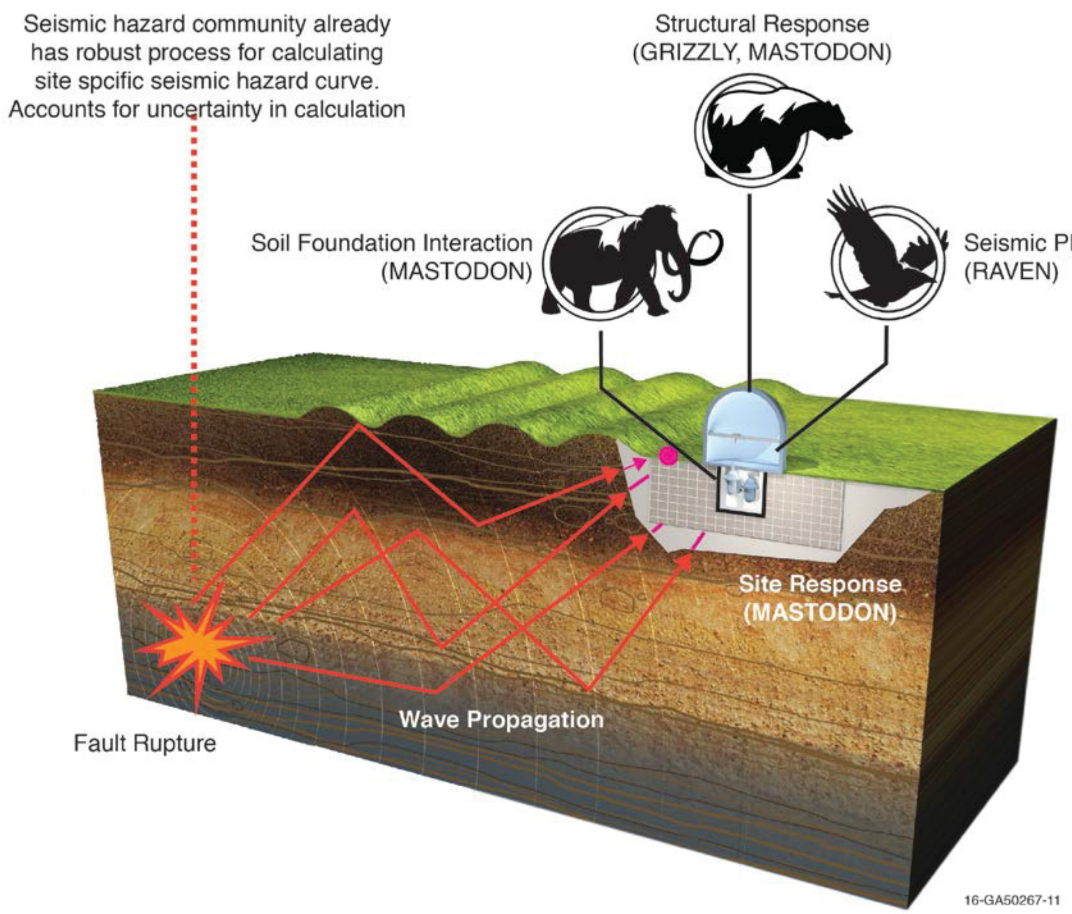

Figure 5: Source to site seismic wave propagation

2.1 Verification and Validation and the Role of the External Hazards Experimental Group in RISMC Toolkit Development

Oberkampf and Trucano (2008) states that verification is "…the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the mode" and validation is "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model." An important R&D element of the RISMC Toolkit is the verification and validation of the advanced external hazard (seismic and flood) analysis tools developed. These tools, and their associated methods, are intended to provide best-estimates of both hazard probabilities and nuclear facility response under a range of hazard inputs in order to gain accurate risk insights and better ensure nuclear power plant safety during and after beyond design basis events. The computer codes must be able to accurately predict the response of NPPs during earthquakes, as well as the flow of water during flooding. The numerical tools will have mathematical equations that describe physics behavior, such as seismic wave propagation and water flow over complex geometry. Tools that will require validation include nonlinear time domain seismic analysis, such as MASTODON, which is under development in the MOOSE framework, and smooth particle hydrodynamic (SPH) analysis codes, such as Neutrino, the flooding simulation tool.

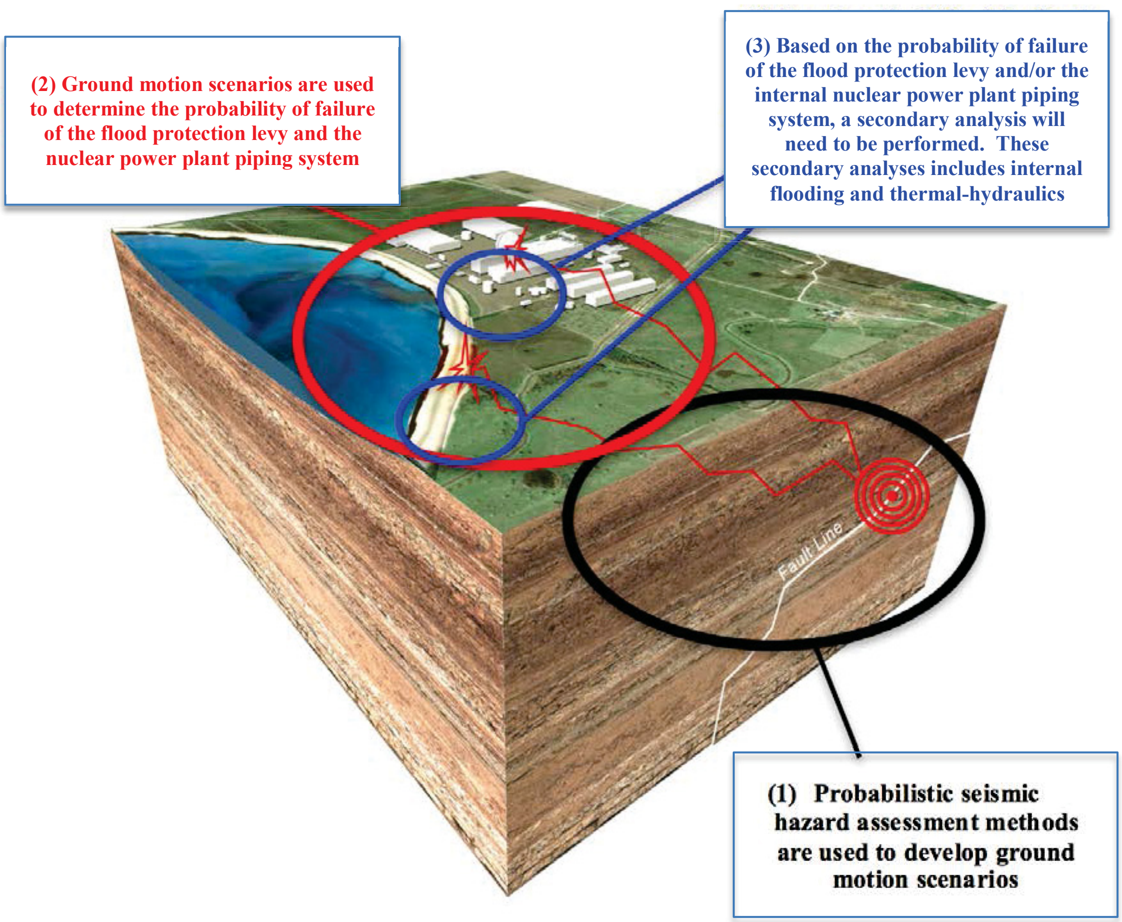

Figure 6. Multi-hazard problem solved using RISMC computational framework

It is important, in assessing and improving the tools developed, to identify the individual physics-based parameters that contribute the predictive capability of the tool. Each physical parameter can be validated starting at the element or unit level (i.e. the level at which an element has uniform properties and is under uniform loads) and the numerical capability improved. The next step is to validate tools and model performance at a benchmark tier (or tiers) with a slightly more complex experiment. Finally, system-level tests can be performed to validate the numerical code's predictive capability. Figure 7 lays out this process for developing and validating the predictive capability in numerical tools intended to perform site response and nonlinear SSI seismic analysis.

Currently, there is limited data available to perform validation of the tools and methods being developed in the RISMC Toolkit specific to external hazards. The ERG-EH is being developed to obtain high quality, large-scale experimental data validation of RISMC tools and methods in a timely and cost-effective way. The group of universities and national laboratories that will form the ERG-EH (which is ultimately expected to include both the initial participants and other universities and national laboratories that have been identified) have the expertise and experimental capabilities needed to both obtain and compile existing data archives and perform additional seismic and flooding experiments. The resulting databases to be developed will be used to validate the advanced external hazard tools and methods.

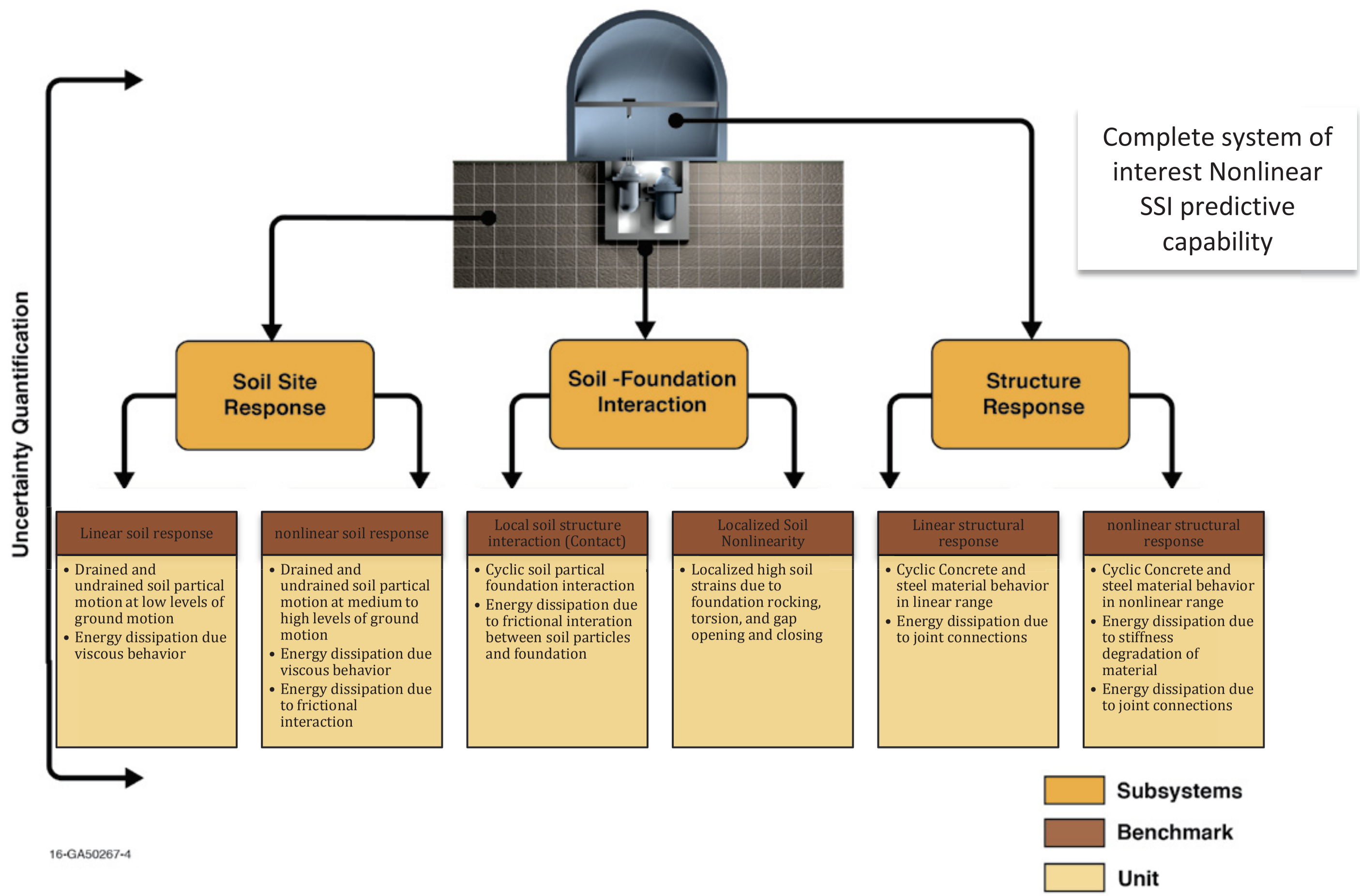

Figure 7: Validation process for developing a predictive capability of site response and SSI numerical tools

3. PROCESS FOR VERIFICATION AND VALIDATION

A process for verification and validation of numerical tools is discussed in this section. The process is needed to ensure quality control and for tools to have a predictive capability. Oberkampf (Oberkampf *et al.* (2004) presents a process to follow when performing V&V of numerical tools. This process should account for uncertainties throughout, both material property uncertainties such as modulus of elasticity and stress, strain, also account for uncertainties in experimental testing boundary conditions. The verification process compares the computation model and solution with the correct answer in the range of interest (Figure 8).

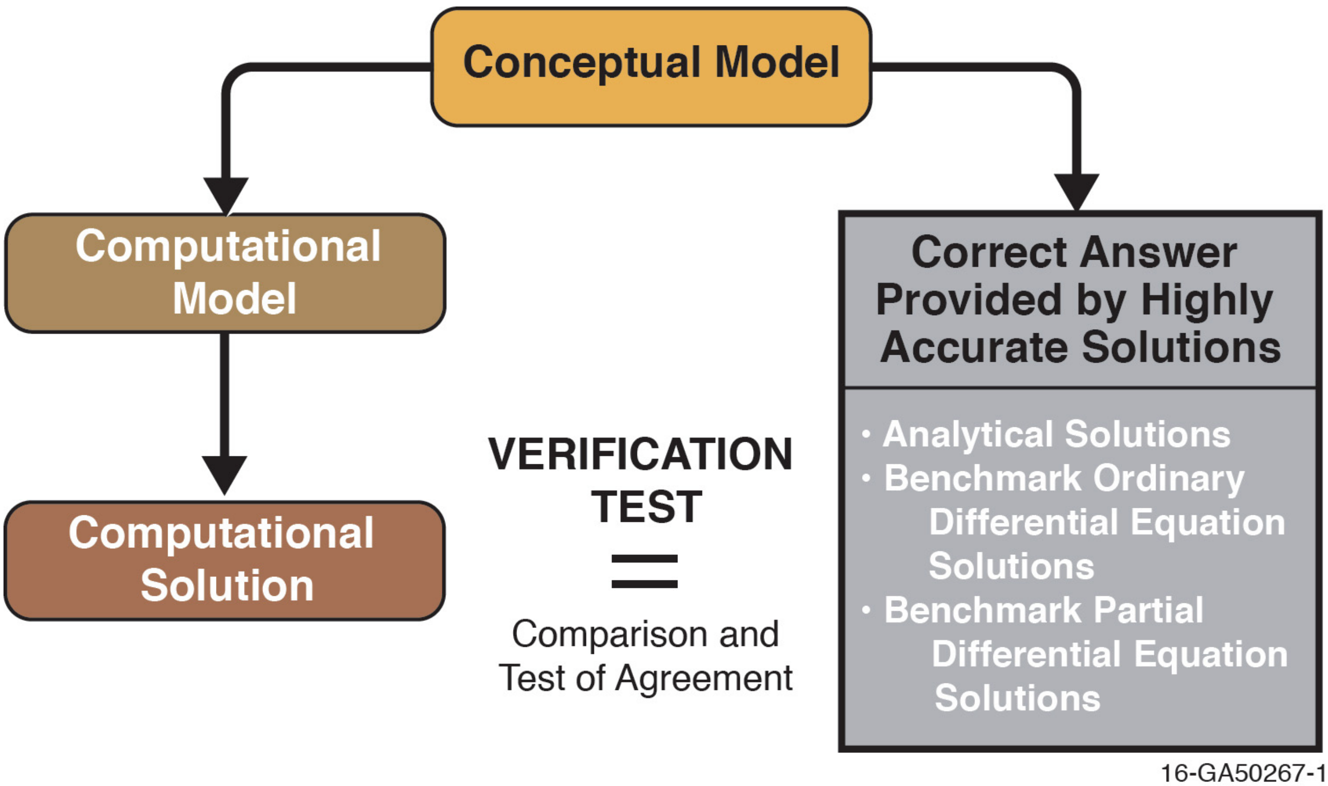

Figure 8: Verification process (Oberkampf *et al.* (2004))

The validation process is a process that develops confidence in the predictive capability of computation codes to model real world phenomena in ranges of interest. This process includes comparing computation models and solutions with increasingly complex experimental data. The data needs to start with unit problems, move onto benchmark cases, and finally validate the complete system of interest. Figure 9 outlines this process.

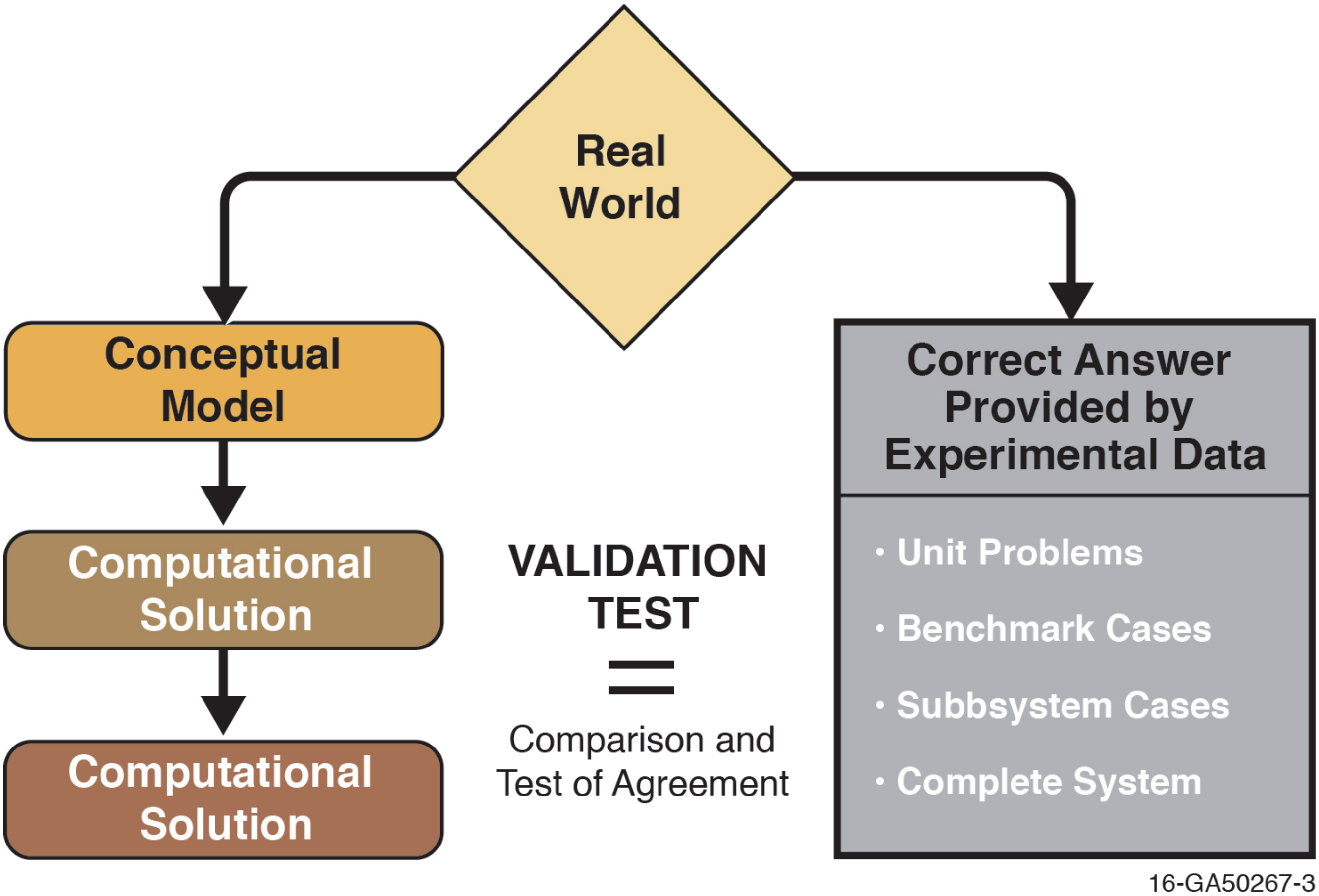

Figure 9: Validation process (Oberkampf *et al.* (2004))

The unit tier validation activity should have the following characteristics:

- Physical
    - Simple, non-functional, hardware fabricated
    - Simple geometry
    - No coupled physics
    - Simple physical response measure
- Measured data
    - All model inputs measured
    - Most model outputs measured
    - Many experimental realizations
    - Experimental uncertainty given on all quantities

The benchmark tier validation activity should have the following characteristics:

- Physical
    - Special, non-functional, hardware fabricated
    - Simplified geometry and material properties
    - Little coupling of physics
    - Very simple BCs and ICs
- Measured data
    - Most model inputs measured
    - Many model outputs measured
    - Several experimental realizations

    - Experimental uncertainty given on most quantities

The subsystem tier validation activity should have the following characteristics:

- Physical
    - Functional, system hardware
    - Little or no coupling of subsystems
    - Some physics coupled
    - Simplified BCs and ICs
- Measured data
    - Some measurement of model inputs
    - Some measurements of model outputs
    - Few experimental realizations
    - Experimental uncertainty given on some quantities

The system tier validation activity should have the following characteristics:

- Physical
    - Actual system hardware
    - Actual geometry and material properties
    - Complete coupling of physics
    - Actual BCs and ICs
- Measured data
    - Very limited measurement model inputs
    - Very limited measurements of model outputs
    - Very few experimental realizations
    - Little or no estimate of experimental uncertainty

The concept behind this process is to identify the individual physics parameters that contribute to developing a predictive capability. Each physical parameter can be validated at the unit tier and the numerical capability improved, the next step is to validate at the benchmark tier with a slightly more complex experiment, finally system tier test can be performed to validate the numerical code predictive capability. This process is applied to the seismic soil-structure interaction system and described in Figure 7. This figure lays out a process for developing a predictive capability in numerical tools to perform site response and SSI analysis.

3.1 Phenomena Identification Capabilities of the External Hazards Experimental Group

It is important to identify the physical processes that are expected to have significant effects on seismic and flooding behavior at or around NPPs. As an example this process is applied to the cyclic response of soils. A Phenomena Identification and Ranking Table (PIRT) used to identify the physical phenomenon, how important the response of the phenomena is to the system, and level of confidence in the current numerical models. The physical phenomena that need to be investigated experimentally for validation are listed in the PIRT as shown in Table 2.

Table 2: Phenomena Identification and Ranking Table for identification of behavior need to model soil used in nuclear facility analysis

Phenomenon	Importance to response of interest	Level of confidence in model
Frictional interaction of soil particles	High	Medium
Dilatency of soil	High	Low
Viscous damping behavior of soil at low levels of shaking	Low	Medium
Cyclic Mulitdirection effects of soil	High	Low
Soil saturation	Medium	Low
Wave passage effects in soil	High	Low

Friction interaction of soil particles is very important since this behavior dissipates energy during shaking. Experimental data has been gathered on frictional interaction of soil particles however little data exists on cyclic frictional interaction and how that interaction dissipates energy. Dilatency or volume change of soil is also important. Volume change of soil can occur during shaking due to compacted soil particles moving on top of one another creating an increase in volume and decreasing shear stiffness. Experimental observations from torsional shear tests and resonant column tests indication that at low levels of soil shear strain that there is a small amount of viscous damping. Direct shear tests on soil are typically performed in 1D. It has been shown that 2D effects are important to the cyclic response of soil (Kammerer, 2002).

4. ROLE OF EXPERIMENTAL TESTS IN NUMERICAL CODE VALIDATION

There are several near term tests already planned and actively underway to gather data to validate both seismic and flooding models. This information will be used to validate numerical seismic and flooding tools under development.

4.1 Seismic Testing

As discussed in Coleman *et al.* (2016) two tests are currently being planned to validate nonlinear seismic behavior, 1) nonlinear soil behavior (site response), and 2) gapping and sliding behavior between the foundation and the soil.

Test 1) will use a large-scale geotechnical laminar box to experimentally capture wave passage effects. The large-scale geotechnical laminar box at the University at Buffalo will be used for experiments designed to provide the appropriate large-scale test data. Once performed, this will be the first large-scale laboratory-controlled study available for validation of site-response analysis tools. Tests are scheduled to be performed in the summer of 2016.

Figure 10. Large-scale laminar box at the University of Buffalo

Gapping and sliding can significantly affect SSC response in nuclear structures, but these phenomena are currently not well understood. The Seismic Research Group at INL will be conducting experiments to provide (1) insight into the physics of gapping and sliding between soil and concrete and (2) data that will be used to calibrate the soil-foundation contact models used in nonlinear SSI simulations.

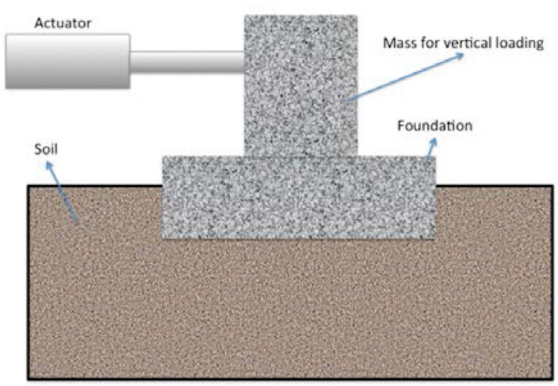

Figure 11: Proposed gapping and sliding experimental test setup

4.2 Flooding Testing

For flooding tests, initial tests of simple components will be run and the complexity of the experiments increased over time to include more prototypic components. The first phase focuses on the initial application and includes modifications such as instrumentation specific to the needs of flooding data collection and expansion of an existing water reservoir. These modifications will allow tests for water rise and spray scenarios. The later phase of testing will focus on wave impact testing. While the first phase is underway, research is being conducted into wave impact event generation and simulation.

Programmatic testing-related research is also being conducted in parallel with the testing described above. The program strategy will be to begin with conducting a large number of simple tests using simple components utilizing existing or easy to procure components and testing infrastructure. The goal of these tests will be to develop a qualitative understanding of how different kinds of components such as structural, mechanical, and electrical components behave in various flooding scenarios. As the testing capability increases, the testing methodology and sophistication will increase, building on the experience gained in early testing. Testing with actual NPP components will carry certain higher costs and the testing protocol must be highly refined prior to conducting these tests to ensure the quality of the data is sufficient for use in assessing NPP risks. The program will solicit participation from industry and regulatory stakeholders and procure more complicated and prototypic NPP components. Figure 12, showing damage from Fukushima Tsunami event, provides an example of the damage states of in-situ systems and components that the testing is intended to better understand and quantify.

Figure 12 Flooding Damaged Doorway Example

After the qualitative understanding of component failure is developed in the early stages, fragility curves can begin to be developed that quantitatively describe the failure. A key part of this task is to identify the flooding variable which drives the failure and ought to be distributed in the fragility model. Depending on the component and nature of flood, water height may not always be the strongest variable to consider. Research should be conducted looking at how other factors play a role in failure. Other variables that may be important factors are the hydrodynamic (impulse) loading, and time of submergence. Determining when a component can resume its function after the water has receded may also be an important factor to consider. Once the fragility curves for critical components in the NPP have been developed they can be used to help inform plant stakeholders about the risk posture of the plant to various flooding scenarios. In order to be of use however, this data will need to be tied in with the codes in the RISMC Toolbox (as well as potentially new codes) to model risk informed safety margin.

An effort is also currently underway to test full scale doors using an existing water reservoir. For later tests, it is proposed to use a new larger setup. Flood testing will take on a variety of different forms. The water rise rates in the tank are likely to be a critical variable in understanding how the components fail. For the spray testing and later wave impact testing, large volumes of high velocity water coming from a bank of pressurized nozzles will impact the sides of the flooding chamber.

Additional testing will be conducted to assess the ability to simulate the hydraulic loads from high velocity waves using new approaches. Most open channel wave impact machines utilize a ram and even large facilities are only capable of simulating waves in the 5 foot range. An effort is underway using numerical models to determine if water transients can be developed in a *closed* channel system that simulates the hydrodynamic loading of a 10 foot by 10 foot section of a 20 foot tsunami wave. The effort is currently using a computational fluid dynamics code to map pressure forces to rigid bodies interacting with waves. One closed conduit concept being evaluated is depicted in Figure 13 and involves the rapid introduction of a large item (grey in color) to a reservoir which would generate the impulse necessary for the wave simulation.

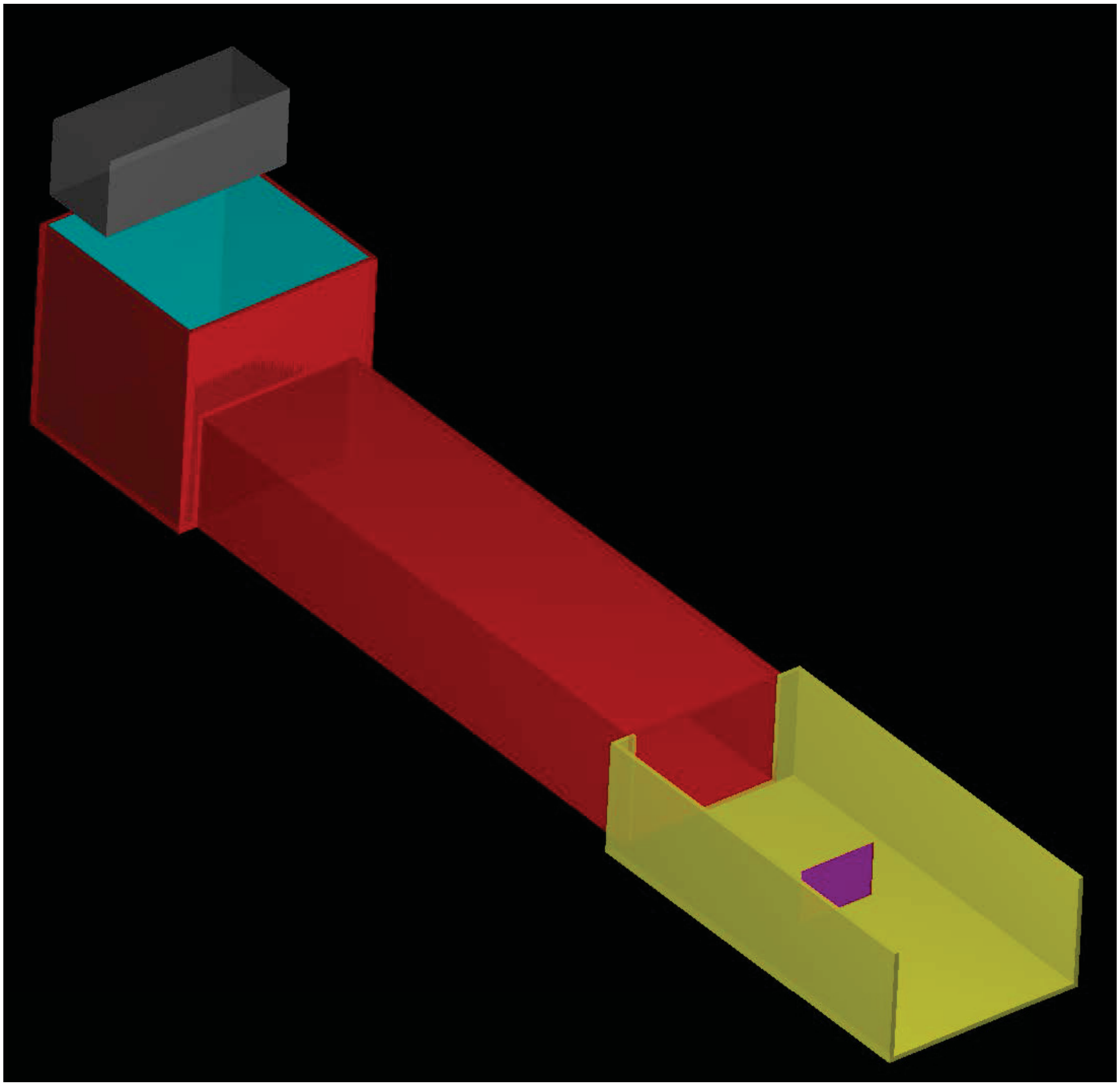

Figure 13. Closed Conduit Wave Generation Concept

Numerical simulation results will be compiled and used as the input to the design effort of the wave generation machine. A small scale prototype of this machine will be built and tested to verify its functionality. In more advanced tests, the wave impact machine will supply a short duration, high pressure slug of water, which will be capable of failing a component. An instrumentation and control system for this machine will be required as it will be desirable to monitor and vary the conditions of the wave impact tests.

Figure 14 illustrates the types of tests that will be performed for the flooding fragility experiments. In this test, a door is tested to failure (due to water building up behind the door). Information is collected (e.g., time of failure, height of water, type of component, nature of the failure, leakage rate of water prior to failure) during the experiment in order to later determine probabilistic fragility models for various component types.

Figure 14. Example of Door Flooding Fragility Test Outcome

5. SUMMARY

This report describes the development plan for verification and validation of the multi-hazad RISMC toolkit. As part of the V&V a new multi-partner ERG-EH coordinated by the Idaho National Laboratory (INL) within the Risk-Informed Safety Margin Characterization (RISMC) technical pathway of the Light Water Reactor Sustainability Program was established.

Currently, there is limited data available for development and validation of the tools and methods being developed in the RISMC Toolkit for external hazards. The data developed by ERG-EH will be stored in knowledge bases within the RISMC Pathway. These knowledge bases will be used to validate the advanced external hazard tools and methods.

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